An Electron EDM Search using Trapped Molecular Ions

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Motivation for e^- EDM Searches

- Direct observation of T-violation (and P-violation).
- Constraints on extensions to the standard model.

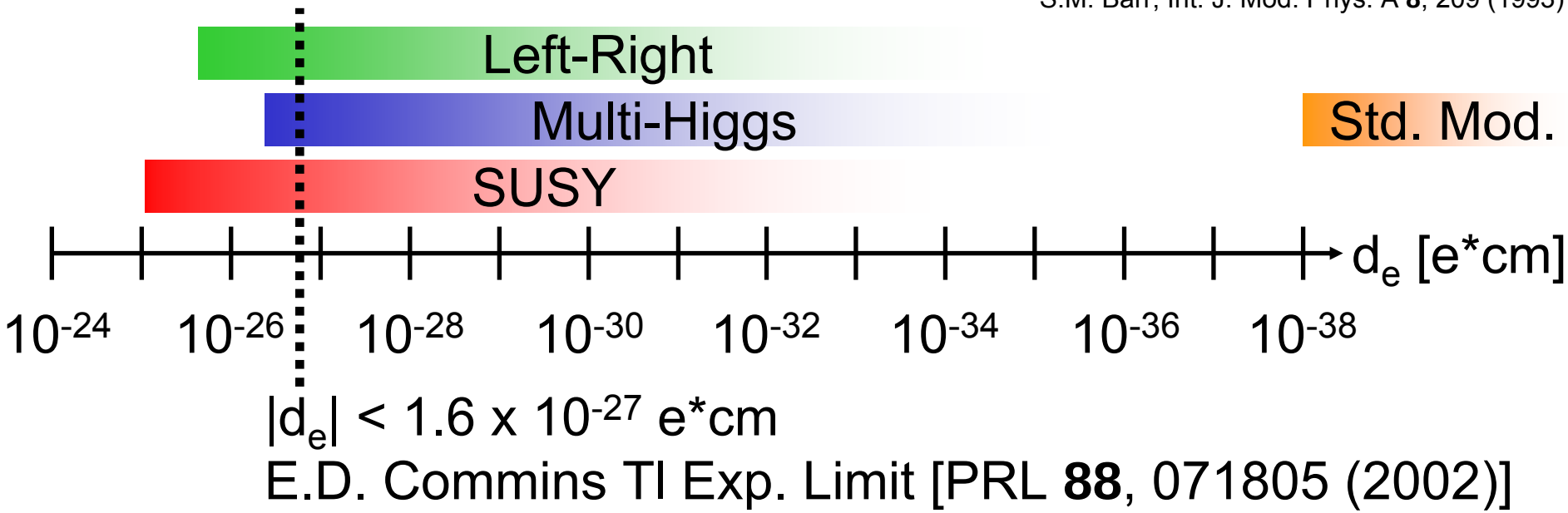
Supersymmetry: $|d_e| \approx \varepsilon_e \left(1\times10^{-25}\, e*cm\right)$

Multi-Higgs: $|d_e| \approx \varepsilon_H \tan\beta \left(1-k\right)\left(5\times10^{-27}\, e*cm\right)$

Left-Right: $|d_e| \approx \chi_\ell \left(3\times10^{-26}\, e*cm\right)$

Standard Model: $|d_e| \approx 1\times10^{-38}\, e*cm$

S.M. Barr, Int. J. Mod. Phys. A **8**, 209 (1993)



Why Use Molecular Ions?

Why use molecules?

- Large internal electric fields.
- Molecules have closely spaced levels of opposite parity → they can be fully polarized with E~100 V/cm.
- Molecules containing heavy atoms give large relativistic enhancement to the electron EDM signal.

Why use ions?

- Ions are easy to trap.
- Potential for long spin coherence times.

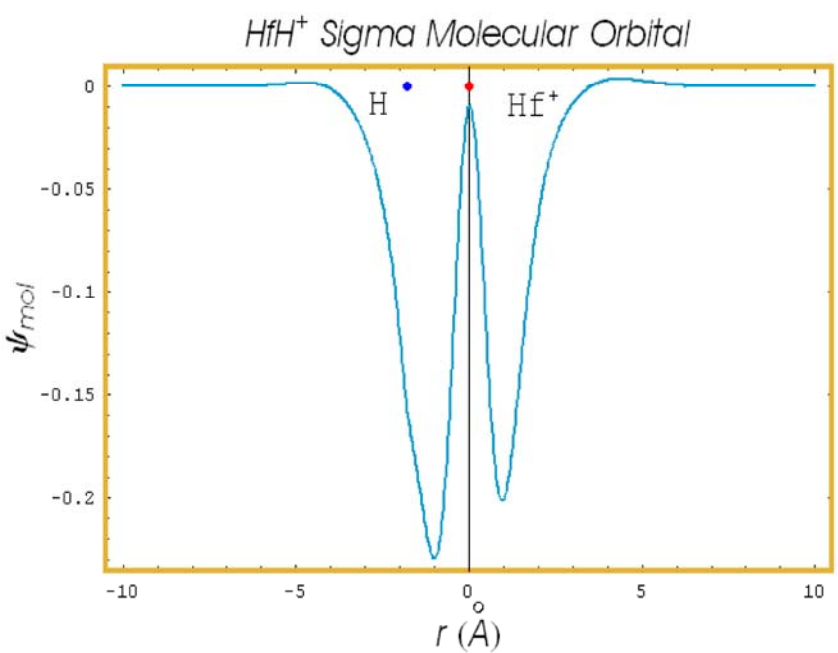
Candidate Molecular Ions

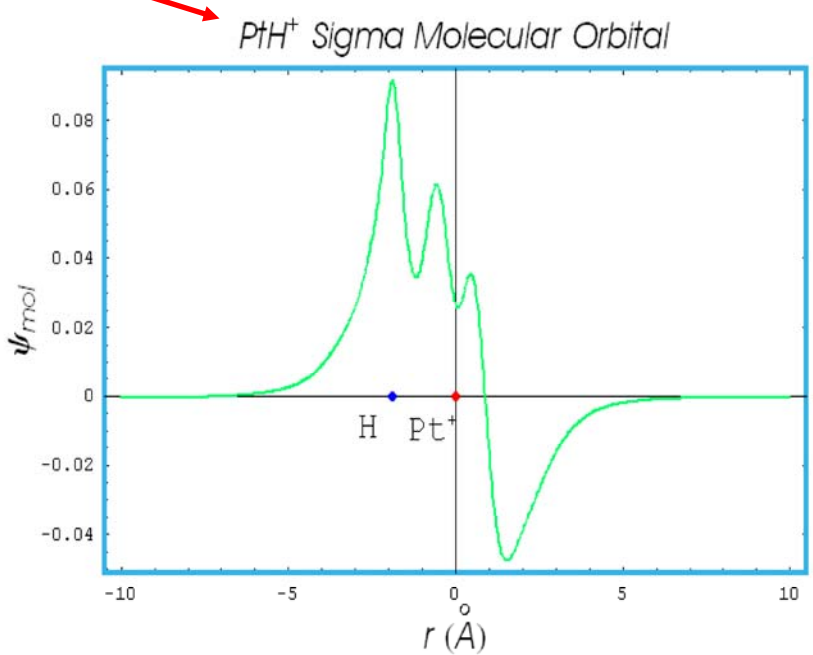
HfH$^+$ and PtH$^+$

- $^3\Delta$ ground states → ~100 V/cm to fully polarize
- strong atomic 6s orbital character → large E_{eff}

$$E_{eff} = -\Omega \frac{16}{\sqrt{3}} \varepsilon_s \varepsilon_p \frac{\alpha^2 Z_i^2 Z^3}{\gamma\left(4\gamma^2 - 1\right)} \frac{1}{\nu_s^{3/2} \nu_p^{3/2}}, \quad \gamma = \sqrt{\left(j + 1/2\right) - \left(Z\alpha\right)^2}$$

Khriplovich & Lamoreaux, *CP Violation without Strangeness*, (1997).





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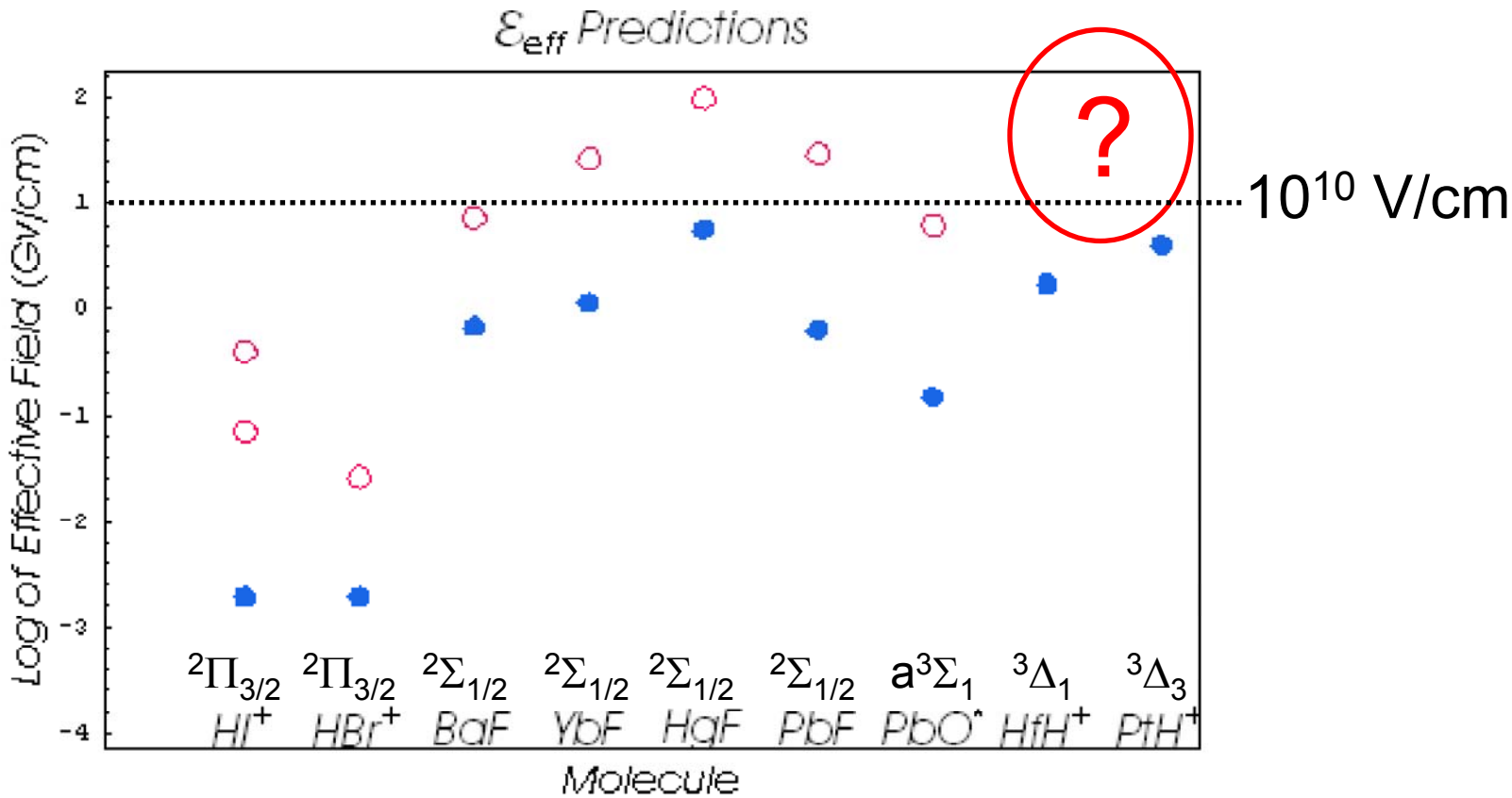
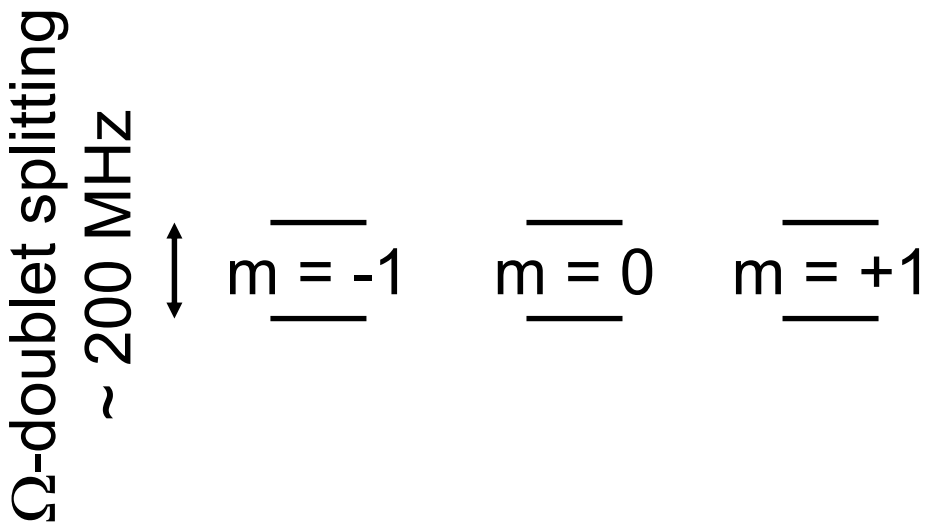


- literature values [arXiv:physics/0506038 and refs. therein]
- 1st order estimate

Experimental Procedure

HfH^+ $^3\Delta_1$ J=1 ground state

- Ω-doublet splitting ~ 200 MHz

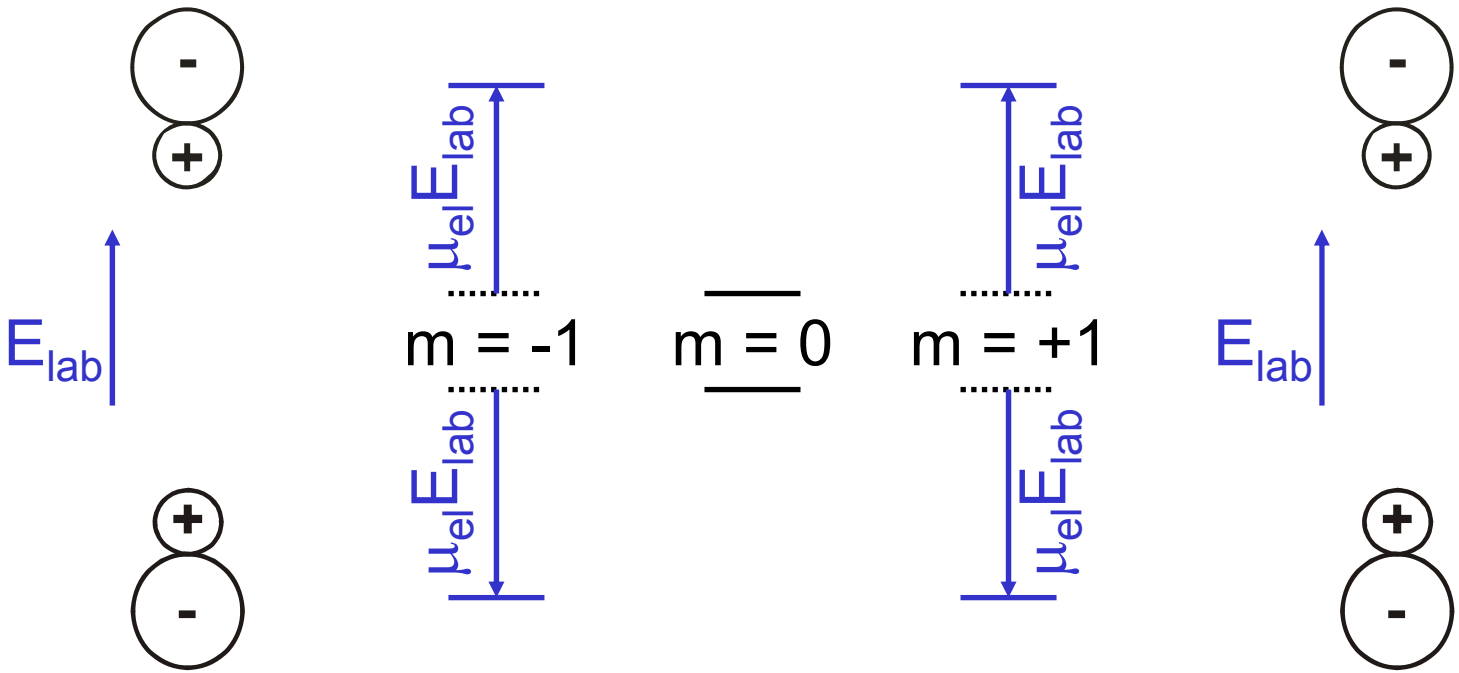


Energies not to scale.
Nuclear spin of ½ excluded for clarity.

Experimental Procedure

HfH^+ $^3\Delta_1$ J=1 ground state

- Electric field mixes states of opposite parity.



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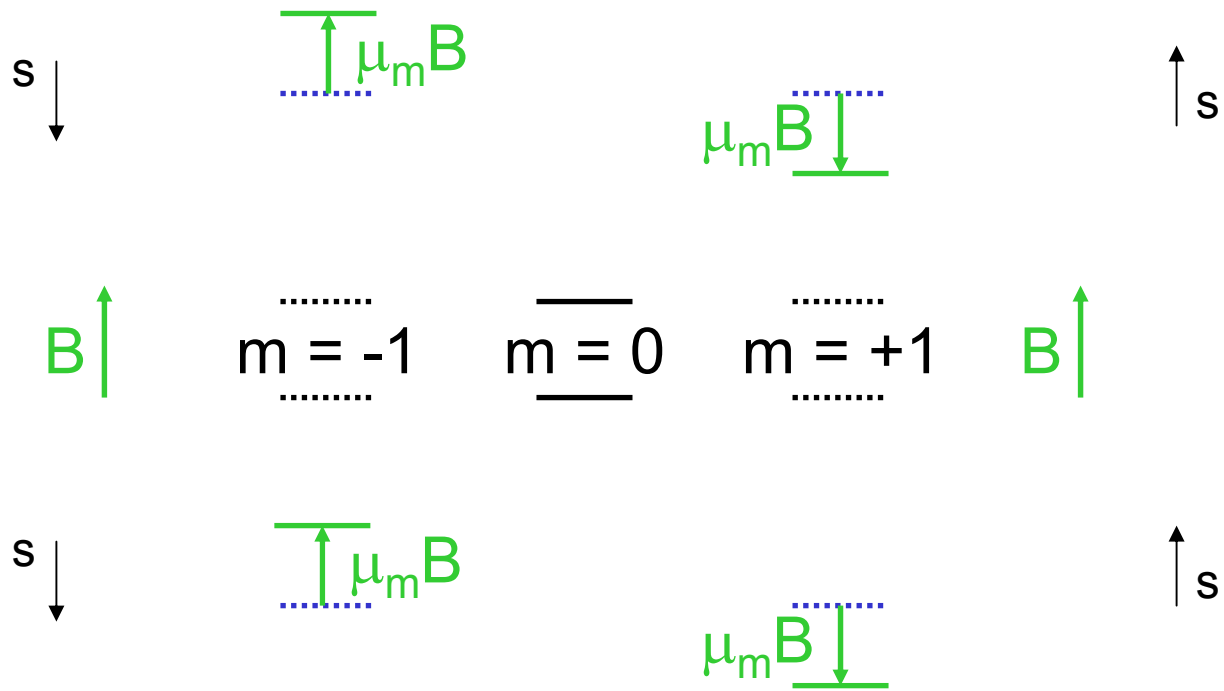
Experimental Procedure

HfH^+ $^3\Delta_1$ J=1 ground state

- Magnetic field lifts degeneracy between |m|=1 levels.

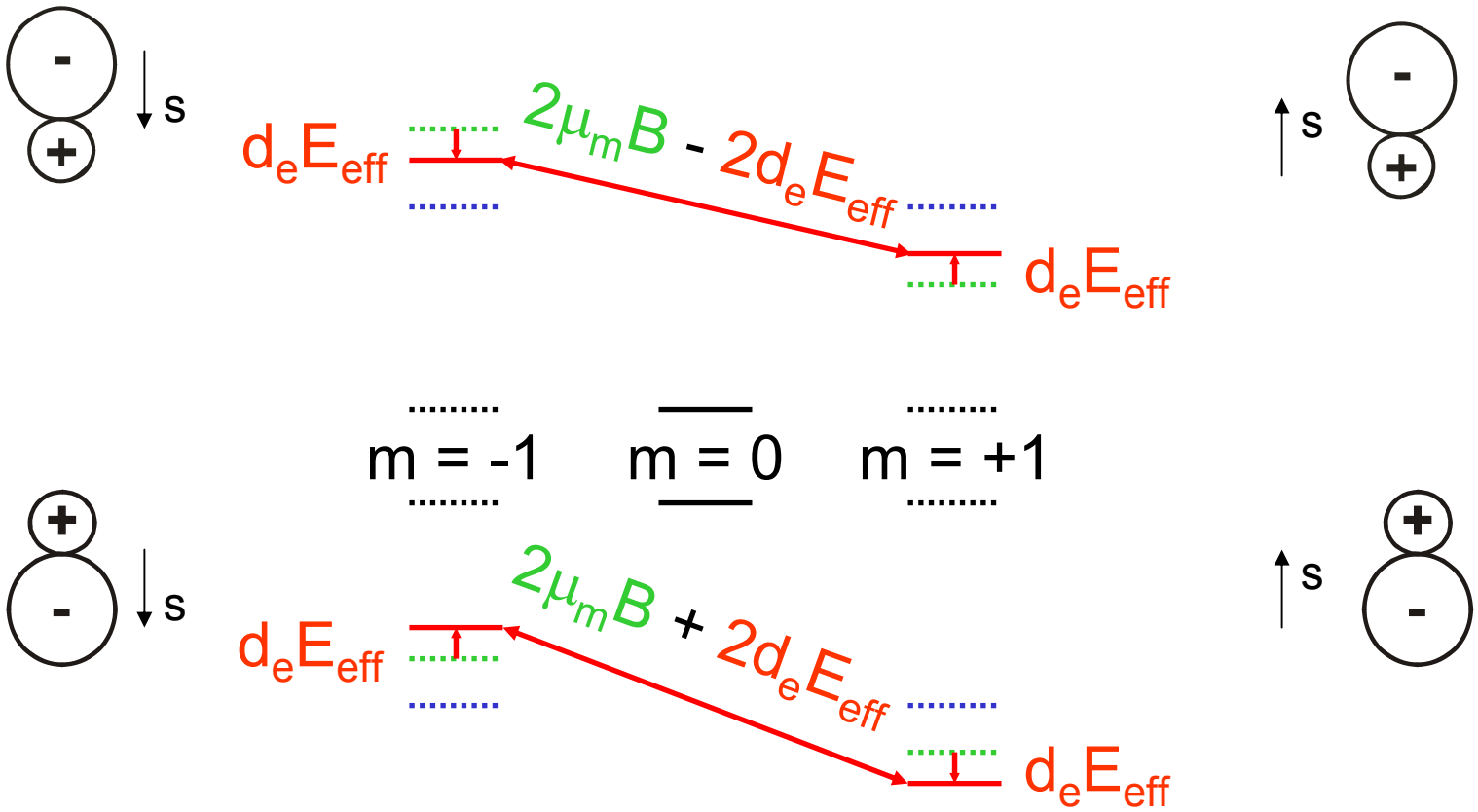


Energies not to scale.

Experimental Procedure

HfH^+ $^3\Delta_1$ J=1 ground state

- Electron EDM shifts the |m|=1 levels in opposite directions in the two Ω-doublet levels.

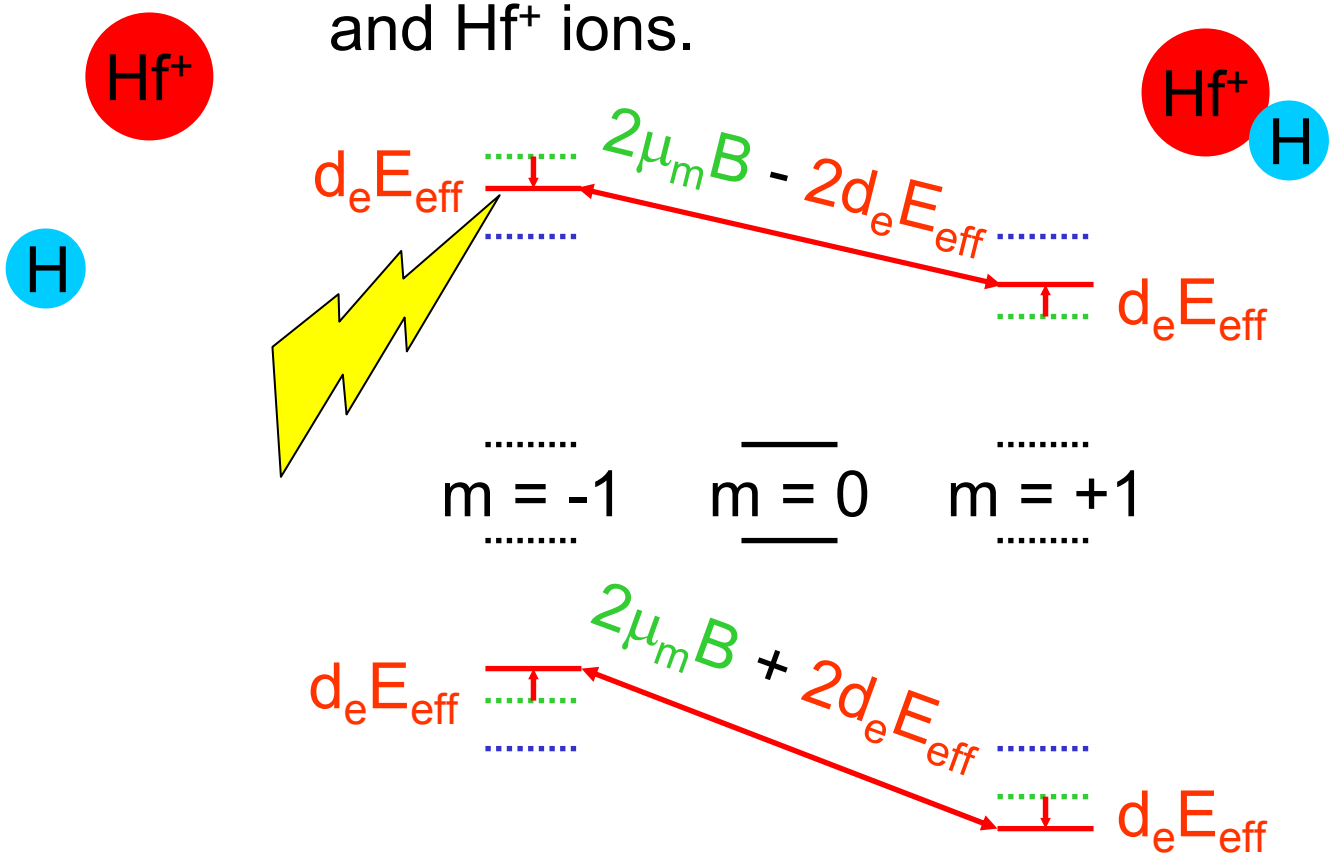


Energies not to scale.

Experimental Procedure

HfH^+ $^3\Delta_1$ J=1 ground state

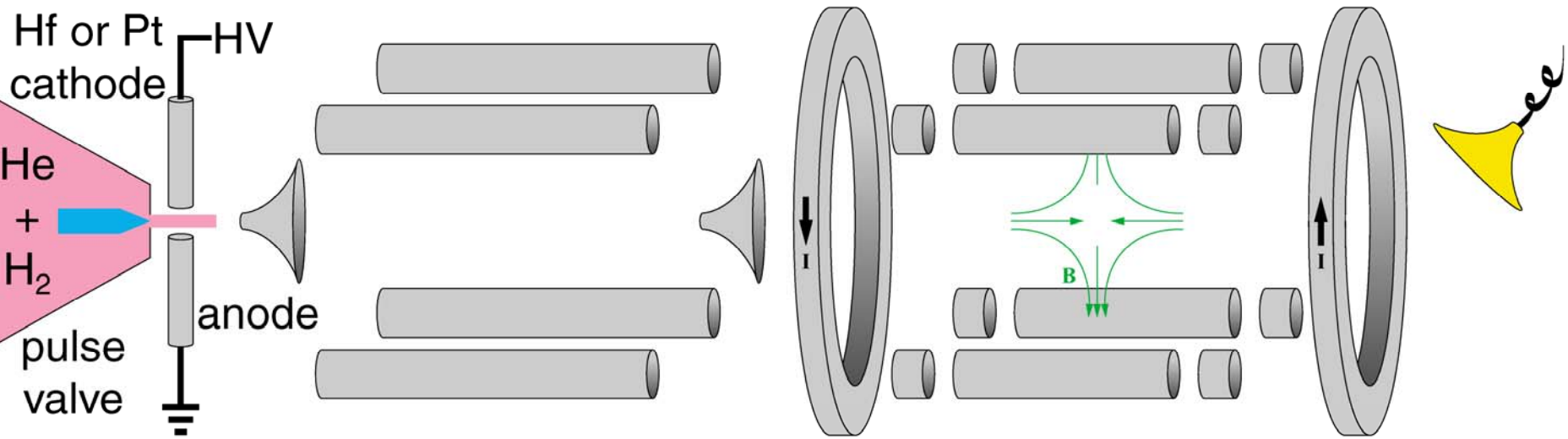
- Perform electron spin resonance (ESR) frequency measurement via the Ramsey Method.
- Photodissociate one spin state and count HfH^+ and Hf^+ ions.



Energies not to scale.

Experimental Setup

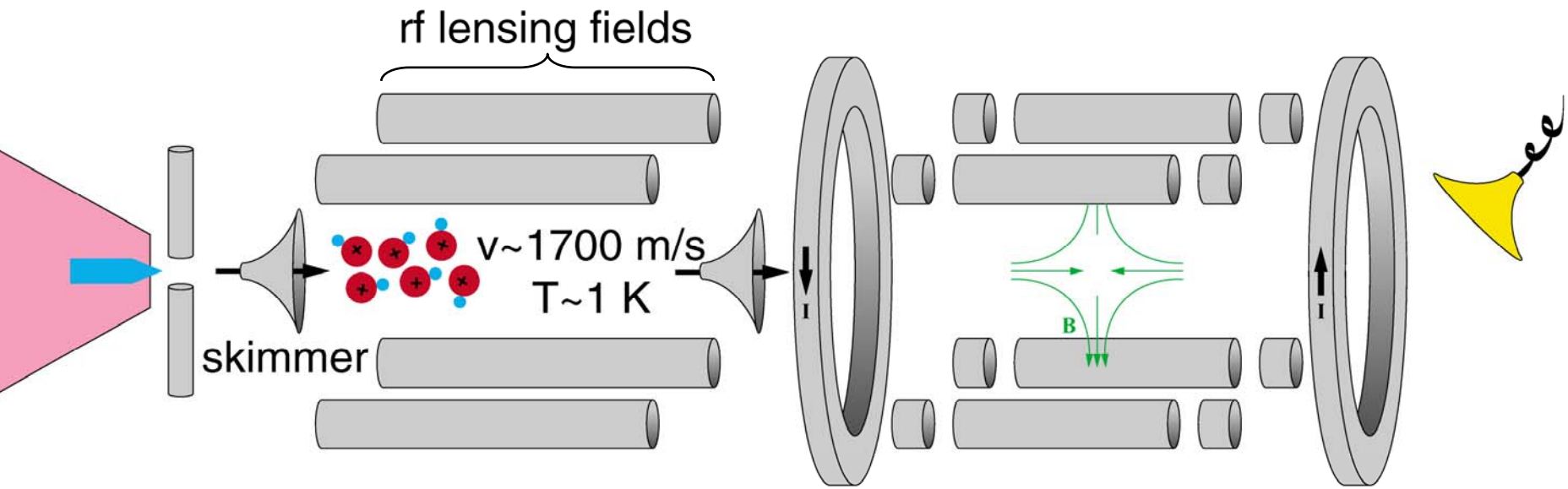
- Discharge or laser ablation creates molecular ions.
- Expansion cools ions to rovibrational ground state (T ~ 1 K).



ion source

Experimental Setup

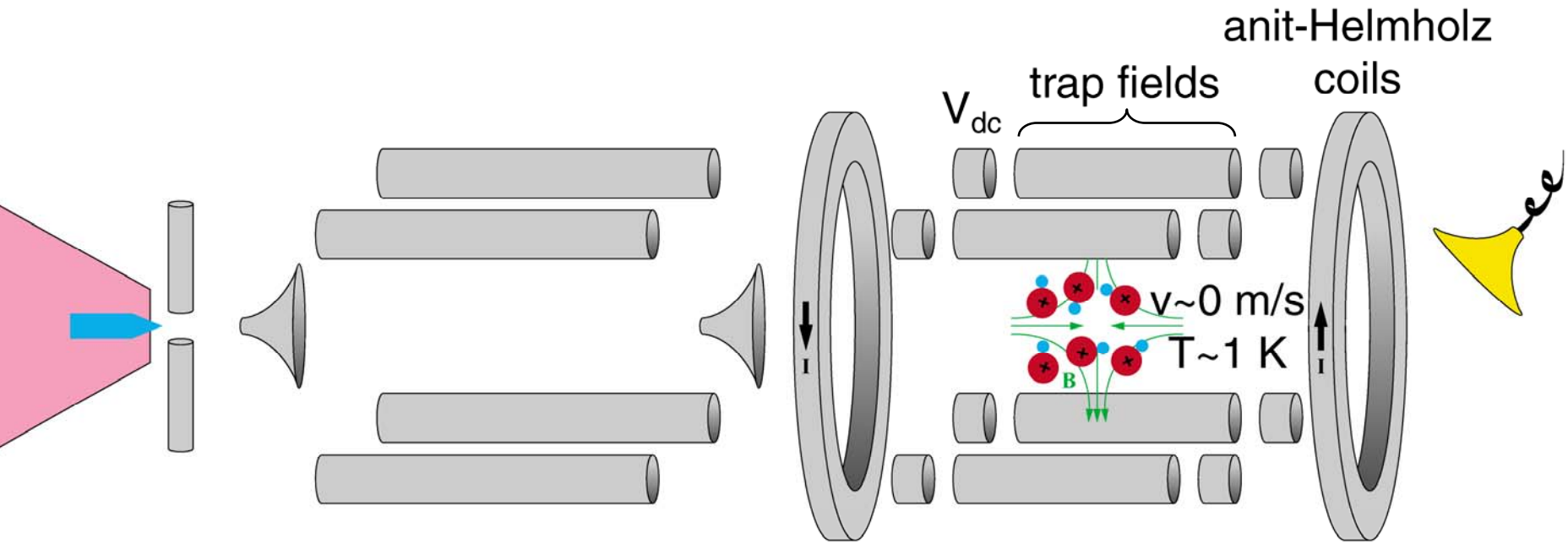
- Discharge or laser ablation creates molecular ions.
- Expansion cools ions to rovibrational ground state (T ~ 1 K).
- Mass selective ion lens focuses only one isotope into trap.



ion lens

Experimental Setup

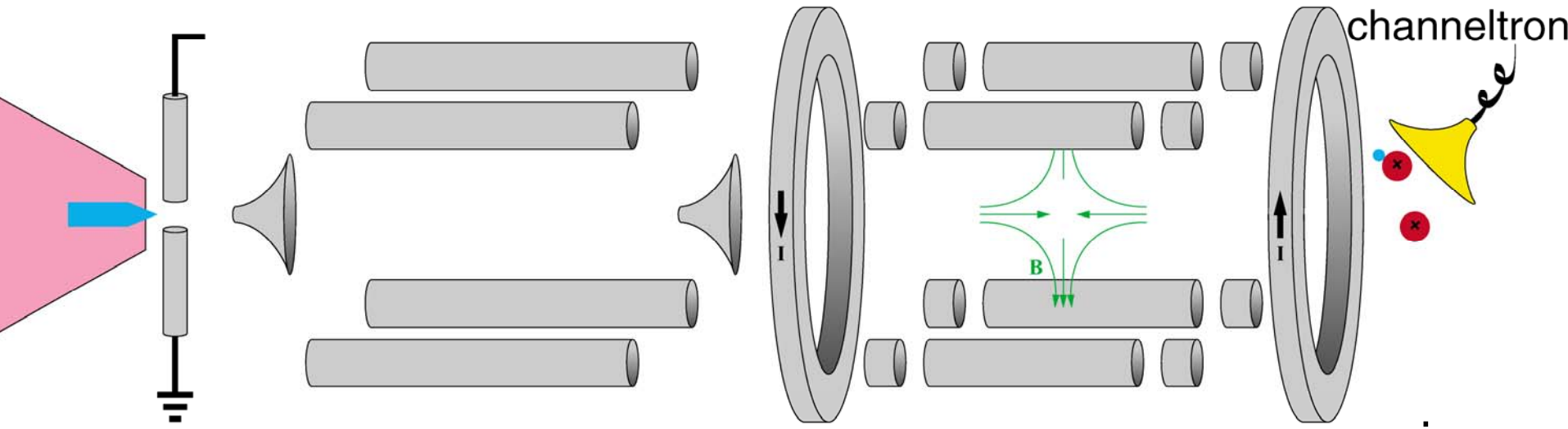
- Linear Paul trap holds ions for measurement.
- Electric and magnetic fields are applied.
- Rf applied for ESR via Ramsey Method.
- Photodissociation laser pulse to detect spin states.



Paul trap

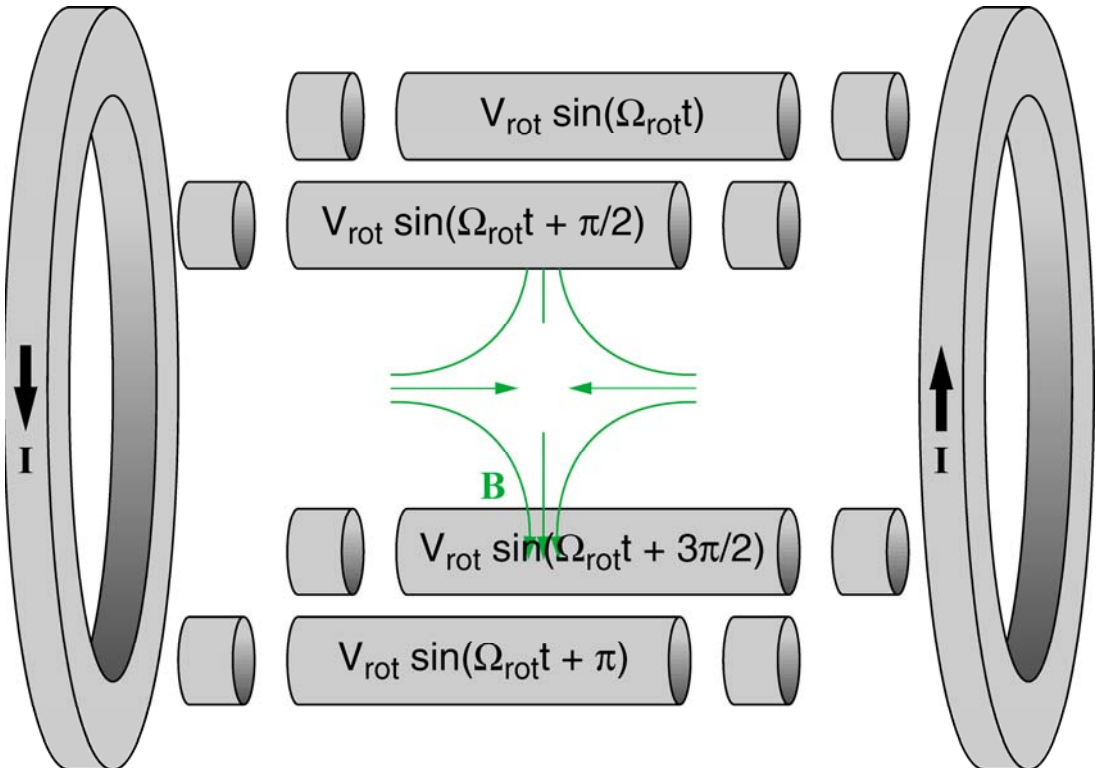
Experimental Setup

- Linear Paul trap holds ions for measurement.
- Rotating E-field and quadrupole B-field are applied.
- Rf applied for ESR via Ramsey Method.
- Photodissociation laser pulse to detect spin states.
- Channeltron counts atomic or molecular ions.



Applying Electric & Magnetic Fields

- Electric field defines molecular quantization axis.
- Use a radial electric field that ***rotates***:
  - Fast enough that the ion motion is negligible.
  - Slow enough that the molecular axis adiabatically follows.
- The magnetic quadrupole field gives rise to a radial magnetic field on the ion's circular orbit, B=B'R.



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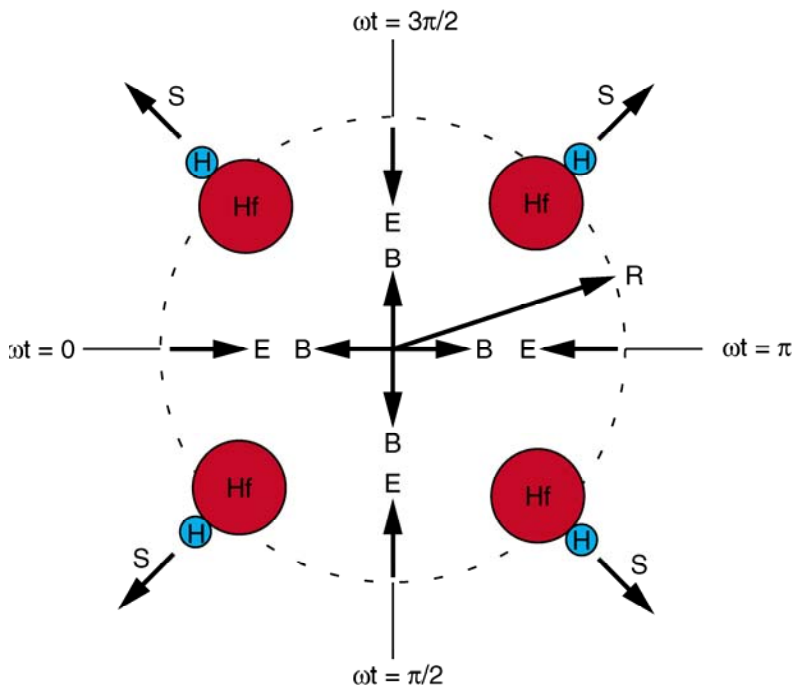
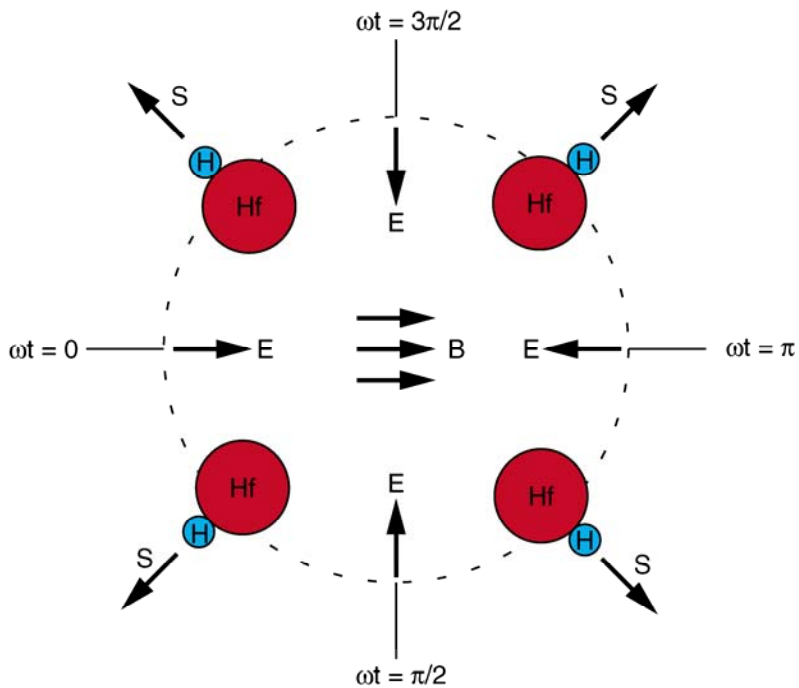
quadrupole B-field



homogeneous B-field



Sensitivity Estimate

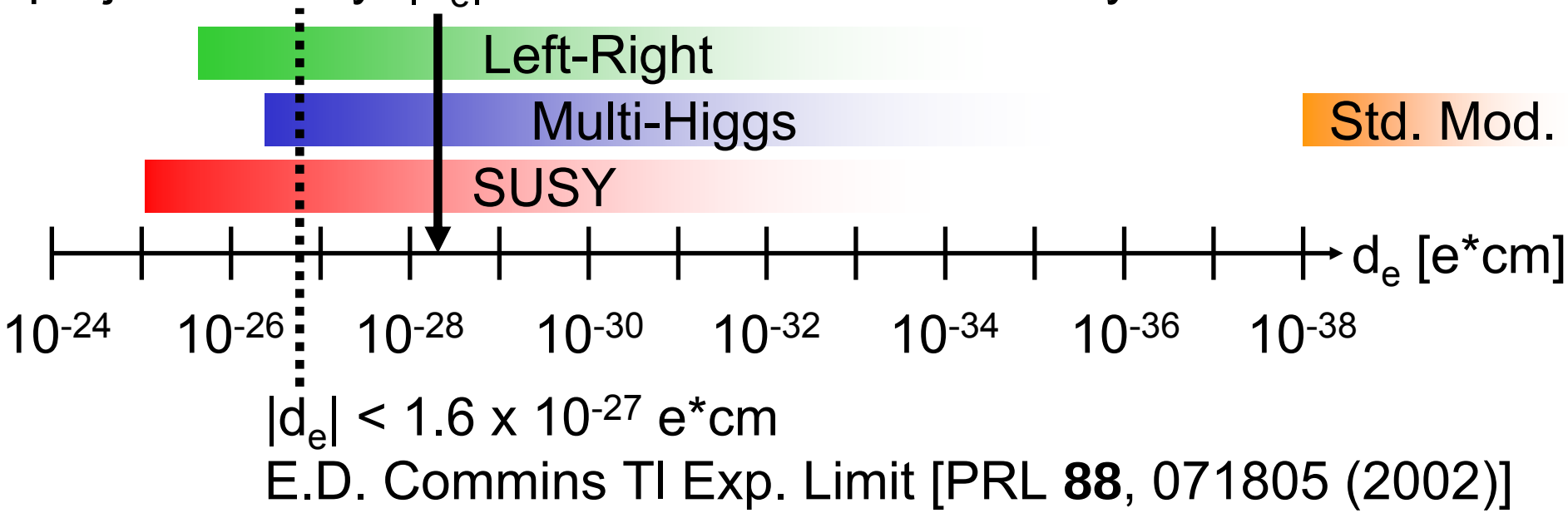
$$|d_e| < \frac{h}{2E_{eff}\tau\sqrt{N}}$$

- N = 150 ions/shot (10^7 ions/day)
- $E_{eff} = 10^{10}$ V/cm
- τ = 1 second

Inverts EDM signal →
- Flip magnetic field direction.
- Change Ω-doublet levels.

Constant EDM signal →
- Change direction of rotating E-field
- Increase magnitude of rotating E-field

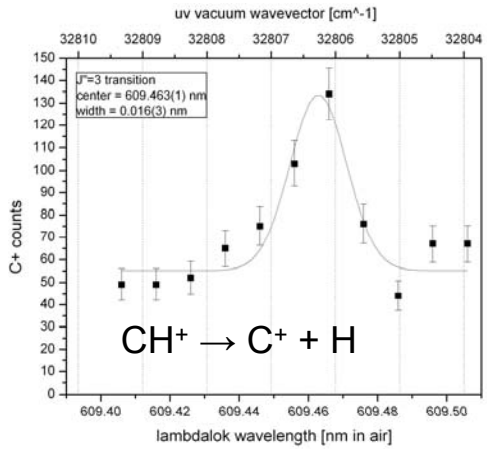
proj. sensitivity: $|d_e| < 6 \times 10^{-29}$ e*cm with 1 day of data

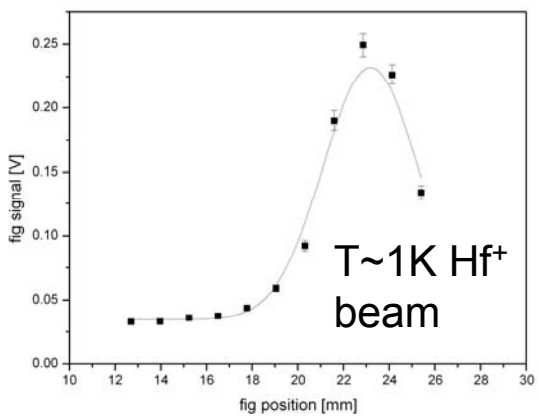


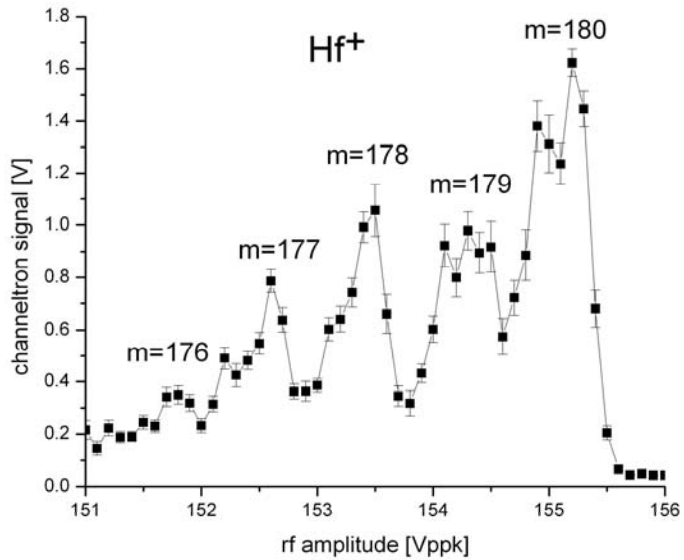
E.D. Commins Tl Exp. Limit [PRL **88**, 071805 (2002)]

Experimental Progress

- Built a linear Paul trap.
- Laser ablation of HfO_2 target to form Hf^+ and HfO^+.
- Photodissociation of CH+ to C+ and H.
- Laser ablated Hf target in expansion, loaded Hf+ ions into trap
- Mass spectrometry of Hf^+ with ~1 amu resolution.







Summary

- Proposed an experiment to search for the electron EDM using trapped molecular ions.
- Expect $E_{eff} \sim 10^{10}$ V/cm.
- Expect spin coherence times ~ 1 second.
- Projected sensitivity ~ 6 x 10^{-29} e*cm with 1 day of data.